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REVIEW ARTICLE

Dust from the Sahara to the American Continent: Health impacts

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Abstract

The Saharan Air Layer is a mass of hot, dry air laden with dust that forms over the Sahara and moves towards the Atlantic Ocean. This air mass contains soil dust particles emitted by the action of winds on the African continent. Between June and August, the large-scale patterns of wind circulation transport dust from the Sahara across the tropical North Atlantic Ocean, affecting parts of the Caribbean, Central America, Mexico, even some regions of the United States, and the Mediterranean and Southern Europe. Between December and April, wind circulation patterns facilitate dust transportation from the Sahara to the northern parts of South America and the Amazon. This dust transportation a phenomenon of interest to geosciences and public health because of the potential health impacts of dust dispersion and circulation in the atmosphere. Thus, we assessed the relationship between exposure to Saharan dust (SahD) and its implications for human health in the Americas. We performed a nonsystematic review in the PubMed, Google Scholar, EMBASE, and Scielo databases of studies published between 2000 and 2020 in Portuguese, English, French, or Spanish using the search words "Saharan dust," or "mineral dust," or "desert dust," and "human health." The available direct air pollutants measurements indicate that the pollution level in the cities affected on a constant and prolonged basis is high versus acceptable standards. Further, this review also showed that the negative health effects of SahD are sparsely studied in the Americas.

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Introduction

The Saharan Air Layer is a mass of hot, dry air laden with dust that forms over the Sahara and moves towards the Atlantic Ocean.[1] This air mass contains particles of soil dust suspended through the winds on the African continent. Dust suspension typically reaches its maximum intensity between mid-June and mid-August, when large-scale patterns of wind circulation transport dust across the tropical North Atlantic, affecting parts of the Caribbean, Central America, Mexico, and even some regions of the United States such as Florida and Texas, the Mediterranean, and Southern Europe. Between December and April, wind circulation patterns facilitate dust transportation from the Sahara to the northern parts of South America and the Amazon.[1-4]

Aerosols from biomass burning can also be disposed of from the African regions of the Sahel and Southeastern Africa, along with Saharan dust (SahD).[5,6] Particles suspended in the atmosphere known as particulate matter (PM), are a complex mixture of minute particles and liquid droplets. Aerosols interact with solar radiation and influence the properties of clouds, regional and global climate, and the hydrological cycle.

Improved knowledge of the characteristics of the particles that leave Africa towards the American continent is a prerequisite for reliable simulations of the effects of aerosols on the planet's energy balance, cloud formation, and precipitation.[5]

SahD is a phenomenon of interest not only to geosciences but also to public health because of the potential health impacts of its dispersion and circulation in the atmosphere. North Africa is considered the planet's primary natural source of PM with different aerodynamic diameters, for example, less than 10 μm (PM_{10})-thoracic particles and less than 2.5 μm ($PM_{2.5}$)-fine particles. Such particles leave the African continent and disperse over the cold, wet marine air, spreading thousands of kilometers.[7]

The interest of the scientific medical community in exploring the health effects of SahD has been increasing in the last two decades. The discovery of a pivotal inhalable component of SahD led scientists to associate it with cardiovascular and respiratory diseases (chronic obstructive pulmonary disease or COPD; sarcoidosis; pulmonary fibrosis), prematurity, general mortality, and a series of infectious diseases (pulmonary coccidioidomycosis; type-A influenza; bacterial pneumonia; and meningitis).[8-14]

We aimed at reviewing articles evaluating the transport and the health impact of dust from the Sahara to the American continent.

Data sources

Nonsystematic literature review, searching the Pubmed, Google Scholar, EMBASE, and Scielo databases for articles published between 2000 and 2020 in Portuguese, English, French, or Spanish, using search words "Saharan dust," or "mineral dust," or "Desert dust," and "human health." The bibliographic survey was carried out between August and December 2020. Initially, 88 scientific articles were found; but only 56 of those effectively addressed the topic of SahD and its repercussions on human health and were selected for the analysis. The database of the National Institute of Amazonian Research (*Instituto Nacional de Pesquisas da Amazônia*, available from https://bdtd.inpa.gov.br/handle/tede/2554?mode=full) was also consulted.

SahD composition and transport

SahD composition is influenced by a wide range of natural and anthropogenic factors. The particle size and conformation are mainly determined by the structure and constitution of the generating rocks and by the physicochemical weathering processes. Additionally, wind speed and atmospheric conditions can also greatly influence dust mixing during transport. The particles found around the dust storms initiation are composed of weather-resistant minerals, such as quartz, titanium, and zirconium. Those most distant from the origin of the storm were composed of clay minerals and phyllosilicates. The particles mostly contained silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), and titanium oxide (TiO_2). Other commonly occurring compounds in the particles were calcium oxide (CaO), magnesium oxide (MgO), sodium oxide (Na_2O), and potassium oxide (K_2O). Several trace elements like zirconium (Zr), strontium (Sr), rubidium (Rb), rare earth elements (REEs) –, evaporated minerals (salt), organic content, pathogens (bacteria, fungi, and viruses), and anthropogenic pollutants (heavy metals, pesticides, sulfate, nitric acid, and polycyclic aromatic carbons) were also incorporated into the dust's matrix and/or surface.[15,16] Aluminum and salicylates mix with the dust particles rich in calcium, sulfur, and heavy metals(i.e., they generally associate with the finer particles with a diameter of less than 1μm [PM_1]).[17]

During the transoceanic voyage, a fraction of the particle's deposits over the ocean and a large quantity of particles remains suspended in the atmosphere and are disposed to the American continent. The ease with which these SahD translocate is because of their size, which allows winds and upward air currents to disperse them over altitudes ranging between 3 km and 7 km.[7]

Impacts of the Saharan air layer

During the study of the impacts of SahD, it is important to highlight the positive as well as the negative aspects.

Positive aspects

SahD is a crushed rock composed of different inorganic chemical elements which constitute the macro- and micronutrients used by plants like phosphorus and nitrogen. Between December and February, intense sandstorm formation in Chad (central-northern Africa) and Niger (central-western Africa) causes the severe transport of phosphorus, iron, and other minerals acting as macro- and micronutrients beneficial for vegetation.[4,15] Thus, SahD plays a critical ecological role in nutrient cycling, contributing to the fertilization of ecosystems in the American continent. The nutrients present in SahD reach the surface through dry deposition or the action of rainfall.[4,15]

The transport of these nutrients contributes to nurturing the Amazon, compensating for the scarcity of nutrients in the region's soil,[8] and a similar ecological effect is also noticed in the ocean, where the growth of phytoplankton, the basis of ocean food chains, is favored by the availability of iron in SahD.[4,18]

Furthermore, the dry and hot conditions of the Saharan air influence atmospheric stability, hindering the formation and intensification of tropical cyclones. When there is dust in suspension, part of the solar energy does not reach the ocean surface, reducing its temperature and hindering water evaporation, which is pivotal for hurricanes and tropical storms formation.[7,19]

Negative aspects

SahD carries toxic elements and other harmful components. Fungi in the dust harm corals, and copper is toxic to certain microorganisms that lie at the base of the marine ecological pyramid.[20]

The suspension and transport of desert PM also worsen the air quality.[20,21] In regions close to the source, on the Cape Verde islands, the influence of SahD storms results in PM_{10} concentrations of around 200 μg/m^3,[21] exerting a major impact on the health of the local population. The air quality guideline for PM_{10} (24 hour average) according to the World Health Organization (WHO) is 50 μg/m^3.[20]

However, the air quality impacts are not limited to regions close to the Sahara. In the Caribbean,[22] PM_{10} concentrations during SahD events can reach 150 μg/m^3. Mendez-Espinosa et al.[23] analyzed the air pollutants in two cities in northern South America (Medellín and Bogotá, Colombia) during the implementation of strict and relaxed lockdown periods because of COVID-19 and showed that the long-range transport of air pollutants affected air quality during the confinement by a SahD event in late June, caused an increase of almost 50 μg/m^3 in the PM_{10}, which reached 168 μg/m^3 in Bogotá and 104 μg/m^3 in Medellín.

In addition to its effect on PM_{10} concentration, the interaction of SahD with local anthropogenic pollutants can also influence the physical and chemical properties of aerosols, with possible impacts on cloud formation and health.[20] Thus, it would become increasingly necessary to have a standardized approach through spatial indicators, potentially useful, to be able to characterize environmental exposures and the health effects of populations that are impacted by the desert dust.[24,25]

Exposure to SahD and health impacts

WHO marks air pollution as a global health priority. It is estimated that 1.4% of the world's deaths result from exposure to PM from both natural sources(like dust lifted from the soil) and anthropogenic sources(like the burning of fossil fuels). The primary sources of atmospheric mineral dust are deserts, and approximately half of it comes from the Sahara.[26]

Outdoor exposure to fine particles is the fifth leading risk factor for death, accounting for 4.2 million deaths and 103.1 million disability-adjusted life years in 2015.[27] Air pollution contributes to the development of pulmonary and cardiovascular diseases and has also been associated with adverse effects on fetal development during pregnancy and lung growth restrictions in children.[28]

The first potential health impact is increased levels of mineral dust, with daily maximums up to 1000 μg/m^3 of PM_{10} close to the sources, whose average daily concentration also reached up to 400–600 μg/m^3 of PM_{10} in receptor sites influenced by transported dust.[20]

Particles with a diameter larger than 10 μm are generally not inhalable, so their harmful impacts are probably external, such as irritation of the nose, skin, and eyes. These particles are not transported over long distances in the atmosphere because of their size. So their impact is restricted to a local scale, close to the sources.[29-33]

On the other hand, PM_{10}, when inhaled, can reach the trachea and the bronchi, and $PM_{2.5}$ particles account for 96% of the PM located in the lung parenchyma that penetrates the gas exchange regions of the lungs and cause a series of damages to the airways, triggering apoptosis, autophagy, and oxidative stress mechanisms.[9]

Ultrafine particles ($PM_{0.1}$) reach the alveoli, pass through the alveolar-capillary membrane, and penetrate the bloodstream, thus causing respiratory (including asthma, tracheitis, pneumonia, and allergic rhinitis) and cardiovascular effects (including stroke)[34-38] and increase mortality and hospitalizations related to these diseases, as demonstrated in several studies.[29-32,39-44]

Other health impacts may be related to the anthropogenic dust load: (1) co-emission of anthropogenic pollutants with desert dust in some cases (because of the influence of emissions from large petrochemical plants and burning) and (2) coating of the dust with anthropogenic pollutants because of the chemical and physical interactions of mineral dust with local pollutants emitted in the receiving region.[15,45]

Indeed, a standardized approach to the methodology for evaluating the short-term health effects of desert dust has been recently proposed.[24,25]

Desert dust particles also carry potential microbial agents, such as bacteria, fungi, and viruses,[28] that survive long-range transport, enriching the airborne microbiome with new soil-derived microorganisms causing health implications.[46,47] Many bacteria isolated from soil dust aerosol samples are highly pigmented, suggesting that, besides the protection provided by clouds, fog, smoke, and desert dust particles, pigmentation also helps protect microbes from ultraviolet (UV) radiation.[47]

Although the virulence factors of many microorganisms that travel with dust are not well understood, their exposure to high temperatures (>39.5°C) and the inhalation of particles implies a significantly higher risk of developing pneumonia.[48]

Rodriguez-Cotto et al.[49] found traces of soluble metals in $PM_{2.5}$ particles and levels of bacterial endotoxins in the SahD samples, both lung cell cytotoxicity determinants, which may trigger an adverse response to inhalable PM in susceptible or predisposed individuals.

There is also a clear temporal correlation between periods of high atmospheric dust content and cases of meningitis (January to April). Extreme dry air could damage the pharyngeal mucosa, thus facilitating bacterial invasion.[11,50]

Recent data revealed that the microbial load associated with SahD is similar between years. Some genera of bacteria and most fungi can form spores, a dormant state that is resistant to desiccation, heat, and radiation.[51]

Sánchez de la Campa et al.[46] found low microbial biodiversity associated with African dust over southern Spain. But microbes cultured on solid and liquid medium suggested that the bacteria transported were alive or presented as spores that could germinate under favorable conditions.

Fungal infection is another concern during sandstorms. Coccidiomycosis is a widespread infection resulting from the inhalation of *Coccidioides immitis* spores, found in the soil and transported through the air. Studies suggest that dust storms that occurring in the southwestern United States are related to this fungal disease, which mainly affects the lungs and can be potentially fatal.[25] Indeed, it presents a bimodal seasonality that coincides with the driest and dustiest months in California and Arizona.[12]

Several mechanisms contribute to the microbial load of African desert dust as it moves across the continents: (1) local winds lift large amounts of arid soil; (2) waste disposal in many parts of Africa is done by burning, contributing bacteria and fungal spores to the rising smoke; (3) trade winds carry the dust over the Atlantic Ocean, where marine microorganisms are suspended in the atmosphere by the action of the waves and addon to the dust.[15]

These intercontinental dust transport events facilitate long-distance dispersion of biological particles associated with the dust. The scarcity of research on this long-distance microbial dispersion stems partially from the common misconception that all microorganisms present in dust clouds are killed by UV solar radiation, lack of nutrients, and desiccation during their journey lasting several days.[15]

Undoubtedly, microbes and pollens are present in SahD. However, only recent data imply SahD events as relevant mechanisms for the transport of aerosol-associated microbes around the globe. The magnitude of the concentrations and the specific microbes associated with dust events remain topics of debate.[47]

Antibiotic-resistant pathogens pose a significant threat to human health. Atmospheric particles can return to the earth's surface through dry deposition, rain, or snowfall. Thus promoting antibiotic-resistant microbe spread over long distances.[52] These antibiotic-resistant pathogens can enter the atmosphere adsorbed on biological aerosols of windborne dust, through wastewater treatment plants, or biomass burning, and subsequently be globally disseminated by jet streams.[47]

Although the detection of microorganisms during long-distance dust transport events indicates of a microbial charge associated with dust, it is still difficult to differentiate between the microflora already present in the local atmosphere and the one that arrived with the dust.[53]

Airborne microbial deposits accompanying extreme weather events pose a realistic threat to ecosystems and public health. Therefore, monitoring the spread and persistence of foreign microbes that travel through storms is a priority, considering the future trajectories of climatic anomalies and the anthropogenic changes in land use in source regions (Table 1).[36,54]

Respiratory problems

SahD can affect air quality in Africa, Europe, the Middle East, and the Americas. It is transported across the tropical North Atlantic in large quantities, almost all around the year. The SahD follows a well-defined seasonal pattern linked to changes in the originating phenomena in Africa and large-scale wind circulation.[35]

The dust carried with this transport is the primary driver of PM_{10} concentrations at monitoring sites of receiving regions during their respective dust seasons, when PM_{10} often exceeds WHO air quality guidelines.[28]

On a global scale, dust can be an important factor for respiratory health. The pathogenic effect of inhaled dust on respiratory tissues can be attributed to the direct physical action of dust particles on the epithelium of human airways, and this effect can be exacerbated by the toxic effects of trace elements and biologically active compounds (bacteria, fungi, pollen, and viruses).[35]

The groups most susceptible to short-term effects of suspended particles are: (1) the elderly, because of their lower immune capacity and the deterioration of general health with aging;[55] (2) individuals affected by chronic cardiopulmonary diseases;[10] and (3) children, whose lungs and airways are not fully developed.[56]

Atmospheric exposure to desert dust carrying fungi can directly affect human health by allergic induction of respiratory stress. Furthermore, fungal spores within these dust clouds can reach both outdoors and indoors downwind ecosystems.[57,58]

The effects of African desert dust transport on asthma and other respiratory diseases have been a topic of attention.[34,59] Samoli et al.[60] found that an increase of 10 $\mu g/m^3$ in the exposure to PM_{10} was associated with an increase of 0.71% in all deaths in Athens, with 75-year-olds being the most affected group.

Likewise, Jiménez et al.[55] observed a significant association between PM_{10} levels and mortality from respiratory diseases among the elderly in Madrid duri ng SahD intrusions days.

López-Villarrubia et al.[40] saw shreds of evidence of an increased risk for hospital admissions because of asthma and COPD in patients exposed to SahD in the Canary Islands. Gutierrez et al.[61] studied the same phenomenon in Miami and documented an increased risk for recurrent acute exacerbations in patients with COPD and PM.[61]

Exposure to high concentrations of PM_{10} because of SahD transport events is associated with an intense inflammatory reaction in the airway mucosa of patients with ischemic heart disease.[10]

Areas affected by desert sandstorms, such as Caribbean communities, are known to have some of the highest incidences of asthma on the planet. SahD associated with seasonal humidity allows the formation of inhalable particles that aggravate asthma among residents of the Caribbean island of Granada.[62] Recently, a relationship has also been documented between African dust and respiratory stress, increased asthma exacerbations and emergency admissions, and increased daily rates of pediatric hospitalization in Trinidad Island.[63] A similar relationship was documented by Cadelis et al.[64] found evidence relating the concentration of PM_{10} and $PM_{2.5}$ contained in SahD to an increased risk for visits to emergency services in children with asthma in Guadalupe. Monteil et al.[22] also documented a significant

Table 1 Relevant epidemiological studies on health effects of Saharan dust exposure.

Reference	City, Country	Dust concentration in dust days $\mu g/m^3$	Study design	Health outcome	Metrics
Alessandrini et al.[30]	Rome, Italy	$PM_{2.5}$, $PM_{2.5-10}$, and PM_{10}	Time-series analysis applying light detection, ranging observations, and analyses from the operational models.	Daily hospitalizations	$PM_{2.5-10}$ and cardiac diseases 3.93% (95% CI, 1.58-6.34). PM_{10} and cardiac diseases 3.37% (95% CI, 1.11-5.68), and cerebrovascular 2.64% (95% CI, 0.06-5.29) and respiratory diseases 3.59% (95% CI, 0.18-7.12).
Cadelis et al.[64]	Guadeloupe Caribbean French's Archipelagus	PM_{10} and $PM_{10-2.5}$	Case-crossover	Visits to emergency department for asthma by children aged between 5 years and 15 years	PM_{10} IR(%): 9.1% (95% CI, 7.1-11.1). $PM_{2.5-10}$ IR(%): 4.5% (95% CI, 2.5-6.5).
Faustini et al.[44]	Spain, France, Italy, and Greece	PM_{10}	Satellite data case-crossover	PM_{10} and mortality	Increase in natural (0.49%), cardiovascular (0.65%), and respiratory (2.13%) mortalities.
Jiménez et al.[55]	Madrid, Spain	PM_{10}, $PM_{2.5}$, and$PM_{10-2.5}$	Ecological longitudinal time-series study	Mortality of organic causes except accidents,and circulatory and respiratory causes	$PM_{2.5}$ concentrations in Madrid displayed a significant statistical association with daily mortality for all causes.
Mallone et al.[42]	Rome, Italy	$PM_{2.5}$, $PM_{2.5-10}$, and PM_{10}	Time-series analysis using light detection and ranging (LIDAR) observations and analyses from the operational models.	Daily mortality and different PM.	$PM_{2.5-10}$ and cardiac mortality (9.73%; 95% CI, 4.25-15.49). PM_{10} cardiac mortality (9.55%; 95% CI, 3.81-15.61).
Perez et al.[29]	Barcelona, Spain	$PM_{1,}$ $PM_{2.5-1}$, and $PM_{10-2.5}$	Case-crossover	Cause-specific mortality: cardio vascular, respiratory, and cerebrovascular.	Significant effects of $PM_{10-2.5}$ for cardiovascular OR, 1.03 (95% CI, 1.01-1.06; $P < 0.05$) and respiratory mortality OR, 1.04 (95% CI, 1.001-1.09; $P < 0.05$).
Renzi et al.[37]	Palermo, Catania, Syracuse, and Messina and three macro areas (North-East, South, and West) Italy	PM_{10}	Time-series analysis	Daily count of cause-specific mortality and hospital admissions: natural, cardiovascular and respiratory cause	Increases of 10 $\mu g/m^3$ in nondesert and desert. PM_{10} (lag 0-1 days) were associated with increases in natural mortality of 0.55% (95% CI, 0.24-0.87) and 0.65% (95% CI, 0.24-1.06), respectively.
Renzi et al.[43]	Sicily, Italy	PM_{10}	Time-series analysis	Daily mortality	IR (%) of nonaccidental mortality equal to 2.3% (95% CI, 1.4-3.1) and 3.8% (95% CI, 3.2-4.4) per 10 $\mu g/m^3$ increases in nondesert and desert PM_{10} at lag 0-5, respectively. Respiratory mortality 8.1% (95% CI, 6.8-9.5).

(continues)

Table 1 continued

Reference	City, Country	Dust concentration in dust days µg/m^3	Study design	Health outcome	Metrics
Reyes et al.[41]	Madrid, Spain	Different PM fractions	Time-series analysis	Hospital admissions	Significant increase in respiratory-cause admissions associated with fractions corresponding to PM_{10} and $PM_{10-2.5}$.
Samoli et al.[60]	Athens, Greece	PM_{10}	Poisson regression models	Mortality	PM_{10} was associated with an increase in all deaths of 0.71% (95% CI, 0.42–0.99).
Shahsavani et al.[32]	Iran	PM_{10} and $PM_{2.5}$	Case-crossover	Daily mortality	Increment of 10 µg/m^3 was associated with 3.28% (95% CI, 2.42-4.15) increase of daily mortality.
Stafoggia et al.[31]	Southern Europe	PM_{10}	Poison regression models city-specific	Short-term associations with mortality and hospital admissions.	PM_{10} associate to increase in natural-case mortality 0.65% (95% CI, 0.24–1.06)
Tobías and Stafoggia[25]	Rome, Italy	PM_{10}	Methods used for dust exposure assessment	Daily mortality	PM_{10} at lag 0 for dust days, 0.4% (95% CI, −0.1-0.8) for nondust days, and 0.6% (95% CI, −0.5-2.1) for desert PM_{10}.

PM_{10}, particulate matter with diameter less than 10 µm; $PM_{2.5}$, particulate matter with diameter less than 2.5 µm; PM_1, particulate matter with diameter less than 1.0 µm; 95% CI, 95% confidence interval; IR, increase of risk.

increase in the pediatric admissions in the 7 days following major SahD events in the Caribbean.

Studies have also shown a relationship between dust storms and allergy and pulmonary fibrosis.[8] Derbyshire suggests that acute exposure to mineral dust may cause silicosis (“desert lung disease.”).[65]

Dermatological problems

If SahD is carried over regions affected by vehicular, industrial, or agricultural emissions, substances such as pesticides, herbicides, heavy metals, and dioxins may be incorporated into the dust. The presence of heavy metals like nickel in dust cause skin irritation. Moreover, dust storm particles exert toxicological effects on human skin by activating the cellular detoxification system, producing proinflammatory and immunomodulatory cytokines, and changing the expression of proteins essential for normal epidermal differentiation.[35]

Conclusion

Information about SahD influence and arrival in different countries is vital for understanding the real health impacts faced by the populations of the affected areas.

The ill health effects of SahD have scantly been studied in the Americas compared with other continents. Limited direct measurements of air pollutants are available to indicate pollution levels in the cities affected on a constant and prolonged basis by SahD. These record-high readings when compared with the WHO air quality guidelines.

Considering the rapid ongoing environmental changes, the constant challenges they create, and the promotion of the necessary preventive measures when these events occur, more interaction between scientific disciplines is evident to answer these questions appropriately; thus, mitigating their impacts on the health of affected populations.

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